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A TIGHT AMORTIZED BOUND FOR PATH REVERSAL

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ABSTRACT

Path reversal is a form of path compression used in a disjoint set union algorithm and a mutual exclusion algorithm. We derive a tight upper bound on the amortized cost of path reversal.

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Let T be a rooted n-node tree. A *path reversal* at a node x in T is performed by traversing the path from x to the tree root r and making x the parent of each node on the path other than x. Thus x becomes the new tree root. (See Figure 1.) The *cost* of the reversal is the number of edges on the path reversed. Path reversal is a variant of the standard path compression algorithm for maintaining disjoint sets under union [5]. It has also been used in a novel mutual execution algorithm [2,6].

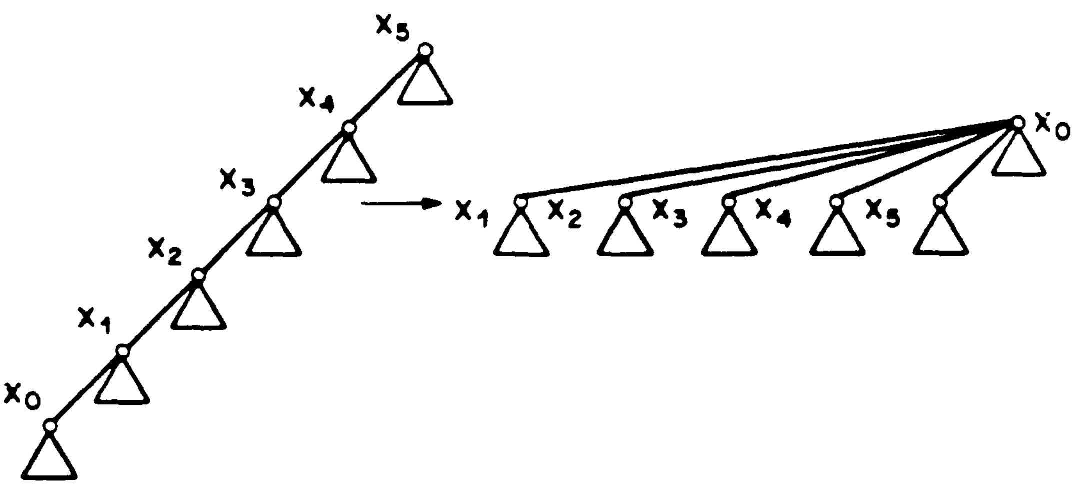

Figure 1. Path reversal. Triangles denote subtrees.

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Suppose that a sequence of m reversals is performed on an arbitrary initial tree. What is the total cost of the sequence? Let $T(n,m)$ be the worst-case cost of such a sequence, and let $A(n,m) = T(n,m)/m$. We are most interested in the value of $A(n,m)$ for fixed n as m grows. As discussed by Tarjan and Van Leuwen [5], binomial trees provide a class of examples showing that $A(n,m) \geq \lfloor \log n \rfloor$ *, and their rather complicated analysis gives an upper bound of $A(n,m) = O(\log n + \frac{n \log n}{m})$. Ginat and Shankar [2] prove that $A(n,m) \leq 2\log n + \frac{n \log n}{m}$. We shall prove that $A(n,m) \leq \log n + \frac{n \log n}{2m}$. In the special case that the initial tree consists of a root with $n-1$ children, which is the case in the mutual exclusion algorithm, the bound is $A(n,m) \leq \log n$.

To obtain the bound, we apply the *potential function* method of amortized analysis. (See [4].) Let the *size* $s(x)$ of a node x in T be the number of descendants of x, including x itself. Let the *potential* of T be $\Phi(T) = \frac{1}{2} \sum_{x \in T} \log s(x)$. Define the *amortized cost* of a path reversal over a path of k edges to be $k - \Phi(T) + \Phi(T')$, where T and T' are the trees before and after the reversal, respectively. For any sequence of m reversals, we have

$$\sum_{i=1}^{m} a_i = \sum_{i=1}^{m} (t_i - \Phi_{i-1} + \Phi_i) = \sum_{i=1}^{m} t_i - \Phi_0 + \Phi_m,$$

where a_i, t_i, and Φ_i are the amortized cost of the i^{th} reversal, the actual cost of the i^{th} reversal, and the potential after the i^{th} reversal, respectively, and Φ_0 is the potential of the initial tree. Since $\Phi_0 \leq \frac{n}{2}\log n$ and $\Phi_m \geq \frac{1}{2}\log n$, this inequality yields

$$\sum_{i=1}^{m} t_i \leq \sum_{i=1}^{m} a_i + \frac{1}{2}(n-1)\log n,$$

which in turn implies

$$A(n,m) \leq \frac{1}{m} \sum_{i=1}^{m} a_i + \frac{n \log n}{2m}.$$

* All logarithms in this paper are base two.

We shall prove that the amortized cost of any reversal is at most $\log n$, thereby showing that $A(n,m) \le \log n + \frac{n \log n}{2m}$. When the initial tree consists of a root with $n-1$ children, the bound drops to $A(n,m) \le \log n$, since then $\Phi_0 \le \Phi_m$, and the extra additive term drops out.

Let $x_0, x_1, x_2, \ldots, x_k$ be a path that is reversed, and let A be the amortized cost of the reversal. For $0 \le i \le k$, let s_i be the size of x_i before the reversal. The size of x_0 after the reversal is s_k, and the size of s_i after the reversal, for $1 \le i \le k$, is $s_i - s_{i-1}$. We can thus write A as

$$A = k - \sum_{i=0}^{k} \frac{1}{2} \log s_i + \frac{1}{2} \log s_k + \sum_{i=1}^{k} \frac{1}{2} \log (s_i - s_{i-1})$$

$$= k + \frac{1}{2} \sum_{i=0}^{k-1} (\log (s_{i+1} - s_i) - \log s_i)$$

$$= k + \frac{1}{2} \sum_{i=0}^{k-1} \log ((s_{i+1} - s_i)/s_i).$$

For $0 \le i \le k-1$, let $\alpha_i = s_{i+1}/s_i$. Note that $(s_{i+1} - s_i)/s_i = \alpha_i - 1$. We have

$$A = k + \frac{1}{2} \sum_{i=0}^{k-1} \log (\alpha_i - 1)$$

$$= \sum_{i=0}^{k-1} (1 + \frac{1}{2} \log (\alpha_i - 1))$$

We now make use of the following inequality, which will be verified below: for all $\alpha > 1$, $1 + \frac{1}{2} \log(\alpha - 1) \le \log \alpha$. From this inequality we obtain

$$A \le \sum_{i=0}^{k-1} \log \alpha_i$$

$$= \sum_{i=0}^{k-1} \log (s_{i+1}/s_i) = \sum_{i=0}^{k-1} (\log s_{i+1} - \log s_i)$$

$$= \log s_k - \log s_0$$

$$\le \log n,$$

since $s_k = n$ and $s_0 \ge 1$.

This completes the amortized analysis. We verify the needed inequality by the following chain of reasoning:

$$
\begin{aligned}
& 0 \le (\alpha-1)^2 \\
\Rightarrow\ & 0 \le \alpha^2 - 4\alpha + 4 \\
\Rightarrow\ & 4(\alpha-1) \le \alpha^2 \\
\Rightarrow\ & \log(4(\alpha-1)) \le \log(\alpha^2) \\
\Rightarrow\ & 2 + \log(\alpha-1) \le 2\log\alpha \\
\Rightarrow\ & 1 + \frac{1}{2}\log(\alpha-1) \le \log\alpha .
\end{aligned}
$$

We conclude with some remarks. The definition of the potential function used here has been borrowed from Sleator and Tarjan's analysis of splay trees [3]; it has also been used to analyze pairing heaps [1]. As in the case of splay trees, the upper bound can be generalized in the following way. Assign to each tree node x a fixed but arbitrary positive weight $w(x)$. Define the *total weight* of x, $tw(x)$, to be the sum of the weights of all descendants of x, including x itself. Define the potential of the tree T to be $\Phi(T) = \frac{1}{2}\sum_{x \in T} \log tw(x)$. A straightforward extension of the above analysis shows that the total cost of a sequence of m reversals is at most $\sum_{i=1}^{m} \log(W/w_i) + \Phi_0 - \Phi_m$, where w_i is the weight of the node x_i at which the i^{th} reversal starts and W is the sum of all the node weights.

Choosing $w(x) = 1$ for all $x \in T$ gives our original result. Choosing $w(x) = f(x) + 1$, where $f(x)$ is the number of times a reversal begins at x, gives an upper bound for the total time of all reversals of $\sum_{i=1}^{m} \log(\frac{n+m}{f(x_i}) + \frac{1}{2}\sum_{x \in T} \log(\frac{n+m}{f(x)})$.

It is striking that the "sum of logarithms" potential function serves to analyze three different data structures. We are at a loss to explain this phenomenon; whereas there is a clear connection between splay trees and pairing heaps (see [1]), no such connection between trees with path reversal and the other two data structures is apparent. In the case of path reversal, the sum of logarithms potential function gives a bound that is exact to within an additive term depending only on the initial and final trees. It would be extremely interesting and useful to have a systematic method for deriving appropriate potential functions. The three examples of splaying, pairing, and reversal offer a setting in which to search for such a method.

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